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TITLE: MEAN FLOW AND TURBULENCE MEASUREMENTS AROUND A 2-D ARRAY OF BUILDINGS IN A WIND TUNNEL

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MEAN FLOW AND TURBULENCE MEASUREMENTS AROUND A 2-D ARRAY OF BUILDINGS IN A WIND TUNNEL

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1. INTRODUCTION

In order to predict the dispersion of harmful materials released in or near an urban environment, it is important to first understand the complex flow patterns which result from the interaction of the wind with buildings and, more commonly, clusters of buildings. Recent advances in the application of computational fluid dynamics (CFD) models to such problems have shown great promise, but there is a need for high-quality data with which to evaluate CFD models. This study was performed to fill that need for a limited range of conditions.

High-resolution measurements of the three components of the mean and turbulent velocity statistics were obtained around a 2-d array of model buildings in the USEPA meteorological wind tunnel. In this paper, we briefly review prior field and laboratory experiments on building flows, describe our experimental set-up and measurement apparatus, present the flow measurements, and discuss their significance in relation to current understanding.

2. BACKGROUND

A large number of flow and tracer experiments have been performed around single buildings (e.g., see reviews by Meroney (1982), Hosker (1984), Peterka et al. (1985) and more recent studies by Lee et al. (1991), Snyder and Lawson (1994), Kastner-Klein et al. (1997), and Cowan (1997)). There have been relatively fewer measurement campaigns around groups of buildings. For two buildings, much of the basic understanding of the flow in the urban street canyon has been obtained through tracer dispersion and smoke visualization experiments. Field experiments by Johnson et al. (1973), Dabberdt et al. (1973), DePaul and Sheih (1985), Yamartino and Wiegand (1986), and Kitabayashi (1992) all confirmed the presence of a large vortex circulation within the urban canyon, although there was some disagreement under what conditions the vortex would form and what the controlling factors were for the vortex strength. These differences can probably be attributed to differences in the building configurations and meteorological conditions, and to uncertainties in the measurements.

Even fewer field experiments have been performed for obtaining flow fields around groups of buildings. A very nice study by Depaul and Sheih (1986) measured the vortex circulation using tracer balloons and rapid sequence photography for a street canyon in Chicago. A few wind measurements were also obtained with a hot-wire anemometer. In a street canyon in Tsukuba, Japan, Kitabayashi (1992) measured the horizontal winds at 4 positions along each canyon wall at two heights. Turbulence statisitics were also obtained at 2 sites near the wall using sonic anemometers. Qin and Qot (1993) took horizontal wind speed and wind direction measurements at several positions within urban canyons at 3 sites in Guangzhou City, China. At one site a U-V-W propellor anemometer was used in the center of the street canyon. A quality, long-term dataset was obtained by Rotach (1995) in Zurich that included two vertical profiles in the street canyon and one profile at rooftop. Eighteen months of data were analyzed from six 3-axis sonic anemometers, 12 cup anemometers, two wind vanes, and four temperature sensors. A unique experiment was performed by Nakamura and Oke (1988) in Kyoto where 63 temperature sensors were used to measure the temperature field within a street canyon. Only two sonic anemometers were used, one at the canyon floor and one at rooftop. Data were collected over two 2-day periods. Although the experiments described above contain valuable information, it is difficult to use this data for rigorous CFD model validation due to sparsity of measurements and lack of knowledge of the upstream boundary conditions.

More measurements can, in general, be obtained in wind-tunnel experiments and the upstream boundary conditions can be accurately defined. Flow measurements in urban canyons have been performed by Britter and Hunt (1979), Hussain and Lee (1980), and Lawson and Ohba (1993), for example. In general, the nature of the flow between two buildings of equal height is determined by the ratio of the width between buildings (W) to the building height (H) (Hussain and Lee, 1980). There is also a weak dependence on the cross-sectional

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length of the buildings. As summarized by Oke (1987), a single vortex develops between buildings for skimming flow (W/H < 1), two counter-rotating vortices may develop for wake interference flow (W/H ~ 1.5), and for isolated roughness flow (W/H > 3) the flow field looks similar to the single building case.

Hosker (1987) reported that several studies have shown that a helical vortex will form between two buildings if the wind is within 60 degrees of perpendicular to the building face, otherwise no vortex forms. Several wind-tunnel studies (Wedding et al., 1977; Hoydysh and Dabberdt, 1988; and Theurer et al., 1992) demonstrated that building height differences can significantly change the urban canyon flow field. In addition, peaked roofs and non-rectilinear buildings can alter urban canyon circulation (e.g., Rafailidis and Shatzmann, 1995). Based on smoke visualization studies, Meroney et al. (1996) found that rooftop recirculation zones do not form on a series of buildings of equal height, except for the one furthest upstream.

Wind-tunnel flow measurements for multi-building arrays have been carried out by a few researchers. For example, Roth and Ueda (1998) measured the longitudinal and vertical components of the mean wind and turbulent intensity for staggered and unstaggered cubical arrays using a laser doppler anemometer. Lateral traverses were made at 5 heights at one downwind location within the cubical array and vertical profiles were taken at two locations: directly behind a cube and in the street channel. Similarly, Davidson et al. (1996) obtained multiple vertical and lateral wind and turbulent intensity profiles using a pulsed wire anemometer for staggered and unstaggered cubical arrays. Both Roth and Ueda (1998) and Davidson et al. (1996) found significant wind speed reduction within the obstacle arrays. However, in both cases, the measurements were not sufficiently dense to fully capture the canyon vortex and rooftop recirculations.

Components of the wind-tunnel experiments performed by Raifailidis and Shatzmann (1995), Meroney et al. (1996), and Theurer et al. (1992) and the small-scale field experiments by McDonald et al. (1998) have similar set-ups as described here, i.e., an array of wide buildings. However, the first two experiments and the last one focused primarily on concentration measurements, while the third took mean wind and turbulence intensity measurements above the building tops only. It is our intent to supplement these experiments with high density mean wind and turbulent kinetic energy measurements in and around a 2-d building array.

3. EXPERIMENTAL SET-UP

The experiments were carried out in the wind tunnel of the U.S. Environmental Protection Agency's Fluid Modeling Facility (Snyder, 1979). The wind-tunnel is of the open-return type with a test section 3.7 m wide, 2.1 m high and 18.3 m long. Airspeed in the test section can be varied from about 0.3 to 8 m/s. The ceiling of the test section is adjustable in height to compensate for blockage effects due to large models or to compensate for the growth of a thick floor boundary layer by allowing for a non-accelerating freestream flow. An automated

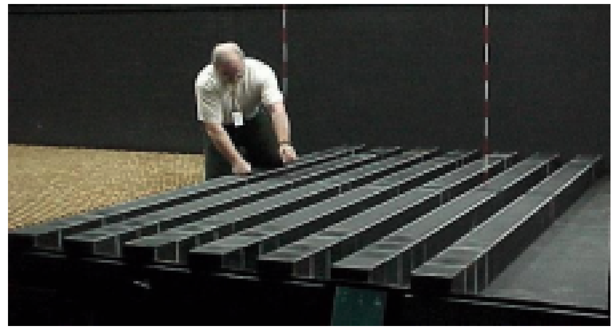

Figure 1. The two-dimensional building array mounted in the wind tunnel.

instrument carriage system provides the capability for positioning a probe anywhere in the test section, acquiring data, then moving to the next measurement location and repeating the process without intervention.

The general setting for the building models was assumed to be an urban environment typical of the downtown areas of modern cities. Ideally, the building height, shape and separation between the buildings should all be varied over the full range of typical values; however, the total number of combinations would quickly become excessive. Based on flow-visualization studies in which many of these parameters were varied, we elected to restrict detailed quantitative measurements to two building configurations, a two-dimensional array as reported herein and a three-dimensional array that will be reported later.

The two-dimensional building array examined in this study consisted of rectangular blocks with equal height and length (H = L = 150mm) and extending from wall-to-wall in the spanwise direction (Fig. 1). The blocks were spaced 1H apart in the alongwind direction. The building models were immersed in a simulated neutral atmospheric boundary layer which was created in the wind tunnel using spires (Irwin, 1981) and floor roughness elements. This combination produced a simulated boundary layer with depth of 1.8m, a roughness length of 1mm, and a power law exponent of 0.16. The array was located 10.9m from the leading edge of the spires to allow sufficient upstream fetch for the boundary layer to grow to equilibrium. While no specific scale ratio was chosen, a representative value would be 250:1, hence the building models would correspond to full-scale buildings on the order of 30 to 40m in height.

Similarity criteria for modeling flow around a building immersed in a neutral atmospheric boundary layer in a wind tunnel require that the Rossby, Reynolds, Peclet or Reynolds-Schmidt numbers, plus a set of non-dimensional boundary conditions, be matched in both model and prototype. Referring to Snyder (1981), the Rossby number can be neglected when modeling prototype flows with a length scale less than about 5 km. Also, provided the model Reynolds number is sufficiently large, it is not necessary to match the Reynolds number, Peclet number or Reynolds-Schmidt product between model and prototype. The reference velocity in this study (3m/s at z=H) was

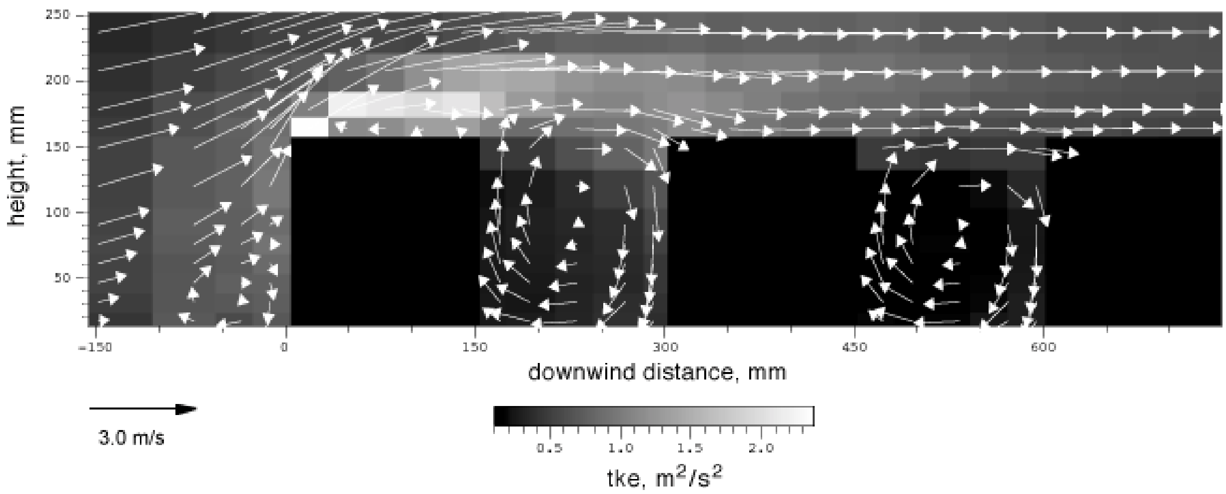

Figure 2. Wind vector and turbulent kinetic energy fields measured along centerline around the 2-d building array in the USEPA meteorological wind tunnel. The first three of seven buildings are shown here.

chosen such that the building Reynolds number was greater than that regarded as the critical value for Reynolds number independence.

A hot-wire anemometer with an X-array sensor was used to measure the mean velocity and turbulence intensity profiles of the approach flow in the absence of any buildings. The hot-wire anemometer is useful when the turbulence intensities are relatively low (e.g. 20% or so), or where the instantaneous velocity vector remains within a cone with a total angle of about 30^o. Significant errors can occur, however, when the hot-wire anemometer is used in high-intensity or reversing flows such as that found near buildings. As a result, measurements within and near the building array were made with a pulsed wire anemometer (PWA, Bradbury and Castro, 1971). The basic principle of operation of the PWA is measurement of the transit time of a heat pulse from a central wire to either of two sensor wires, one located upstream and the other downstream. The central wire is pulsed with a high current for a few microseconds, raising the temperature of the wire to several hundred degrees Celsius and releasing a tracer of heated air which is convected away at the instantaneous flow velocity. The sensor wires are operated as resistance thermometers and are used to measure the time-of-arrival of the heated air parcel. The use of two sensor wires, one on either side of the pulsed wire, ensures that the flow direction is unambiguously determined. While the PWA probe can sense only one velocity component at a time, it can be oriented to measure velocity components in all three coordinate directions. PWA calibrations were performed against a Pitot-static tube mounted in the free-stream of the wind tunnel in the absence of the spires. All PWA measurements were obtained using a pulsing rate of 10Hz and an averaging time of 120 seconds at each measurement location. For each point, the digital time-of-flight signals were first converted to velocity using the appropriate calibration curve for each sensor, then the mean, standard deviation, skewness and kurtosis were calculated for the sample. These statistics were computed for each of 1016 coordinate locations extending from 3.5H upstream of the first building to 7.5H downstream of the last building and to 3H in the vertical.

The velocity measurements were supplemented with measurements of pressure coefficient on the top and on both faces of each building in the array using a capacitance manometer, but are not reported here.

4. RESULTS AND DISCUSSION

Mean flow and turbulence measurements were made down the centerline of the 2-d array of buildings in the direction of the mean wind. Figure 2 shows the mean wind vectors and the turbulent kinetic energy (tke) around and upstream of the first three buildings. Here we see the rotor that forms on the upstream face of the first building and the single large vortex that forms between the buildings within each canyon. The stagnation point on the upstream face of the first building appears to occur at about 1/2 building height in close agreement with the findings of Snyder and Lawson (1994) for a single laterally-wide building. Of particular interest is the separation zone and reverse flow that forms on the first building rooftop, but not on subsequent rooftops. This is in agreement with the smoke visualization studies of Meroney et al. (1996) that showed reverse flow occurred on only the first building for buildings of equal height with W/H = 1. The streamlines above the leading edge of the second building are descending slightly, resulting in stronger downward motion in the first canyon vortex circulation.

Figure 2 also shows a large tke maximum at the leading edge of the first building and an elevated "tail "of large tke values extending above the first rooftop, where the flow jets and shear is strong. A tke "plume" extends downstream above rooftop level and damps out with downwind distance. An interesting feature is the relatively large tke values extending about 1.5 building heights upstream of the first building. A local maximum

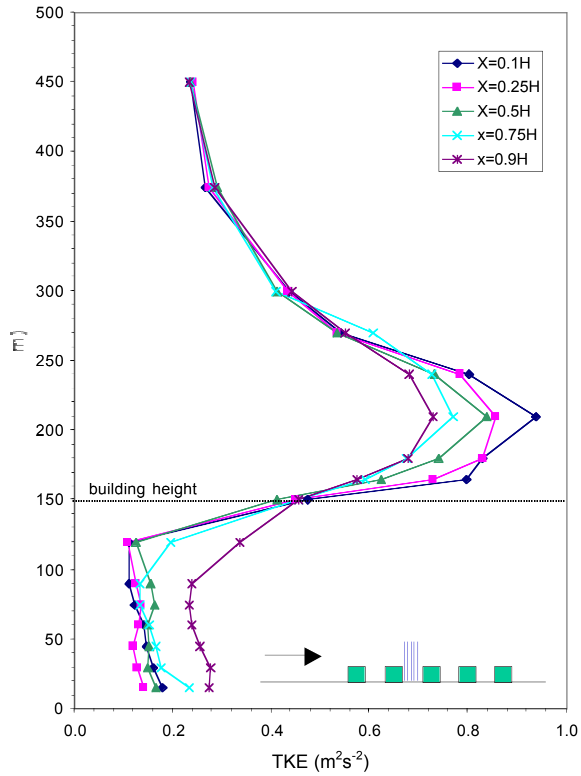

Figure 3. Profiles of tke in the second street canyon. The downwind position x is measured relative to the edge of the upwind building.

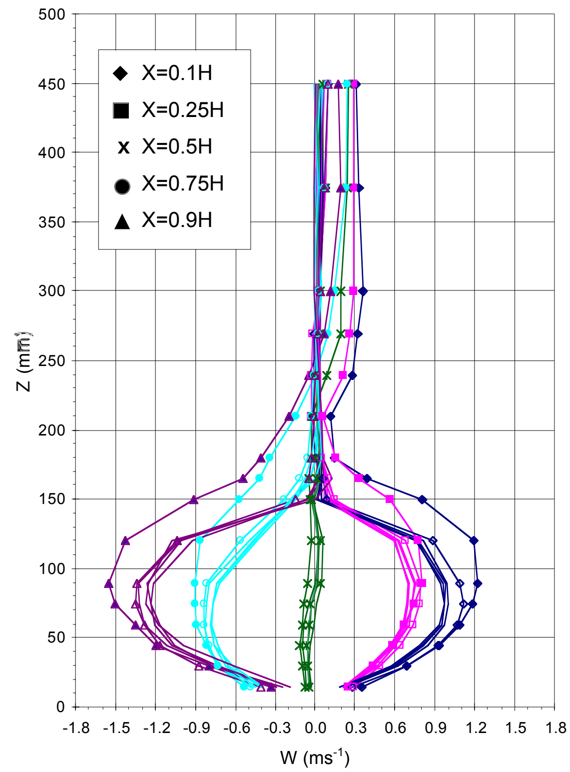

Figure 4. Mean vertical velocity measured at five positions in each canyon. Filled symbols – canyon 1, open symbols – canyon 2, lines – canyons 3-6.

occurs on the upstream face of the first building. (It remains to be seen how the modified k-ε models (e.g., Kato and Launder, 1993; Selvam, 1996) will reproduce this feature, as the traditional k-ε models have been modified to reduce the computed tke upstream of sharp-edged obstacles.) Relatively speaking, the first canyon exhibits the largest values of tke. This may result from advection of a stronger source of tke and/or from stronger shear due to more impingement on the downstream building face. Between the buildings, larger tke values are found on the downstream side of the canyon. Figure 3 illustrates this more clearly, where the tke profile closest to the downstream building wall has nearly twice the tke as compared to the other in-canyon profiles. Above the rooftop, tke values are relatively large with the biggest values upstream. Even over the short distance illustrated here, the above-rooftop tke decays significantly with downwind distance.

Figure 4 shows vertical profiles of the mean vertical velocity in several street canyons. In all cases, the magnitude of the downward motion on the downstream side of the canyon is stronger than the magnitude of the upward motion on the upstream side. From continuity, this suggests that the area of downward motion should be smaller than the area of upward motion. The vertical motions are stronger in the first canyon relative to the other canyons probably due to the slight downward curvature of the mean flow streamlines above the leading edge of the second building (see Fig. 2). Of particular note is that the vertical velocity appears to reach equilibrium relatively quickly: in the 3rd or 4th street canyon. This agrees with the experiments of McDonald et al. (1997) and Hussain and Lee (1980) who found that equilibrium was reached after 4 to 5 building rows based on mean velocity measurements made near rooftop and drag measurements, respectively.

Figure 5 depicts vertical profiles of tke at the center of each canyon. Above the rooftop, the tke is continually decreasing in magnitude with increasing distance from the upstream edge of the first building, the location of most of the tke production. Hence, it appears that it takes more than seven building rows to reach equilibrium *above* building rooftop, whereas, *below* rooftop, the tke reaches equilibrium relatively quickly by the 3rd or 4th canyon.

Vertical profiles of the mean horizontal velocity downstream of the buildings show that the building array impacts the flow at distances greater than x = 7.5H downstream of the last building row (Fig. 6). The reattachment point is between x = 3.5H and 5.5H, presumably closer to the former. Within a half-building height downstream of the last building the velocities are near zero up to about z = 0.8H. Strong reverse flow is found near the ground between x = 1.0H and 2.5H.

The velocity profiles upstream of the building array reveal that the flow at the furthest upstream position (x/H = -3.3) is already being influenced by the building

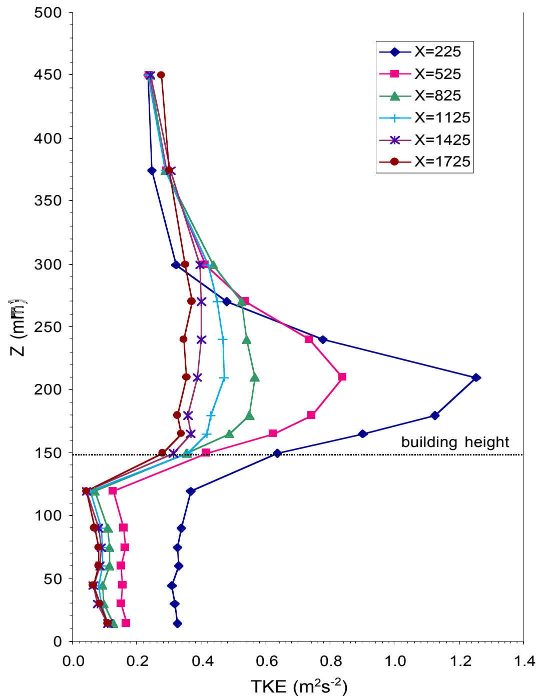

Figure 5. Turbulent kinetic energy profiles measured at the center of each of the canyons in the 2-d building array. Downwind position x in mm.

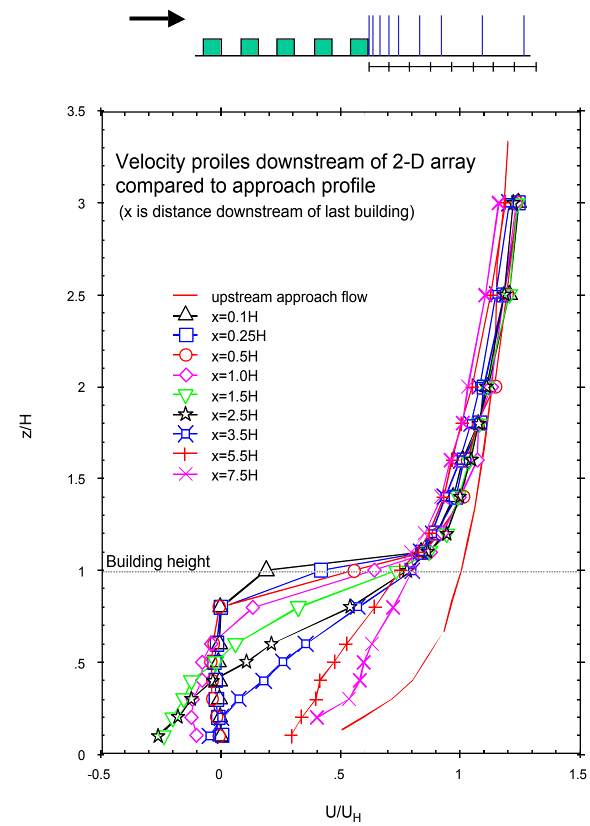

Figure 6. Mean wind velocity profiles measured downstream of the building array.

array (not shown). The small rotor just upstream of the first building identified in Fig. 1 extends approximately 0.5H upstream of the array.

5. CONCLUSIONS

Detailed flow measurements have been obtained in a wind tunnel around a 2-d building array. Measurements include the U, V, and W mean velocity components, the σ_u, σ_v, and σ_w turbulence components, and pressure on building surfaces. Major findings include:

1. separation only occurred on the first rooftop in agreement with the smoke visualization studies of Meroney et al. (1996);
2. above rooftop tke damped out rapidly with downwind distance, but still had not reached equilibrium at building no. 7. The tke and mean flow within the street canyon, however, reached equilibrium by the 3rd or 4th canyon;
3. elevated levels of tke extended about 1.5H upstream of the first building;
4. tke and mean vertical velocity magnitude were found to be higher on the downstream side of each canyon; and
5. the reattachment point was found to be close to x = 3.5H downstream of the last building.

Work continues on analysis of the wind and pressure fields around the 2-d building array. Similar experiments have just begun for an 11x7 array of cubes in order to test the 3-d behavior of CFD codes.

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